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Seeds of promise: Developing a sustainable agricultural biotechnology industry in sub-Saharan Africa

Paul Keese, Ofelia Galman-Omitogun and E. Babafunso Sonaiya

Abstract

In a continent ravaged by poverty, disease and malnutrition, agricultural practices have changed little over millennia. Of all the new technologies recently arisen, molecular biotechnology is one of the few that could significantly improve the livelihoods of the large numbers of people in sub-Saharan Africa. Its impact could exceed that in the developed world, where a multi-billion dollar a year agricultural biotechnology industry has emerged, secured on the back of a highly skilled research and educational sector, extensive biosafety measures, and a strong corporate sector. For much of sub-Saharan Africa, the absence of these foundations constitutes a substantial hurdle to the development of a sustainable biotechnology industry. A critical element is the development of an indigenous and innovative agricultural biotechnology community — one that is responsive to African crops, farming practices and economic imperatives, yet sensitive to local concerns and biosafety issues surrounding use of the controversial GM technology.

Keywords: Agriculture; Biotechnology; Africa; GMO; Transgenic; Recombinant DNA technology.

1. Introduction

As much of Africa struggles to feed itself with technologies fashioned at the dawn of agriculture, the highly mechanized agricultural enterprises of Europe and North America clamour for greater profits and larger global market share. In the developed world, biotechnology is big business, driven by the commercial imperatives of large multinational agrochemical companies with integrated seed company subsidiaries, who control use of the technology through intellectual property rights (IPRs). It is against this backdrop of excess production that Europe and well-fed nations elsewhere contemplate the higher order ethical issues over humanity's newfound ability to create life in its own image and the environmental impact on creatures such as the monarch butterfly.

With more than 40 million hectares now devoted to transgenic crops, agricultural biotechnology is increasing the profit margins in the industrialized world, but for places such as sub-Saharan Africa it promises something far greater. The adoption of certain biotechnology techniques can lead to increased yields without the need of expensive inputs. This is especially important in a continent where food security remains uncertain (Conway and Toenniessen, 1999). Moreover, agricultural biotechnology can offer improved quality, more efficient breeding strategies and novel products. This could improve the health and nutritional status of the population and present new sources of income to alleviate the chronic poverty that plagues much of the African continent. However, in a continent prone to catastrophes, the possible risks also need to be carefully evaluated (Nuffield Council on Bioethics, 1999).

Many challenges lie ahead for sub-Saharan Africa — most of them political, social and economic. The impact of any new technology will be severely limited without supportive government policy, improved infrastructure, upgraded transport provisions, greater credit availability to farmers, and improved market access. In addition, many new technologies do not accommodate social needs and constraints and often fail to be adopted. In this regard, biotechnology represents technology in a seed and as such requires little change in cultural perception and agricultural practices compared to many innovations brought to Africa in the past. The establishment of an enduring agricultural biotechnology industry, indigenous to the region, could be invaluable to development, provided it realises the fruits of the new tools and products, is mindful of the risks, and embraces the interests and needs of the many.

Paul Keese is Acting Head of Biotechnology, International Institute of Tropical Agriculture (IITA), Ibadan.
Ofelia Galman-Omitogun is Associate Professor, Biotechnology, IITA.
E. Babafunso Sonaiya is Professor, Head of Animal Sciences, IITA, Ibadan.

2. Biotechnology tools

Biotechnology (see the Appendix) has been practised for thousands of years, but it is advances in gene technology that have opened up the most opportunities for agricultural improvements and constitute the focus of this article. Agricultural biotechnology based on recent advances in molecular biology falls into two classes: non-transgenic, and the more controversial area of genetically engineered, transgenic organisms. Non-transgenic technologies include: chemical- or radiation-induced mutations followed by selection of agriculturally desirable traits; marker assisted breeding, in which DNA variation linked to an important gene is used to track that gene in breeding populations; germplasm characterization, whereby DNA differences can identify the amount of genetic variation in the large seed banks held in trust; and disease diagnostics (Lande and Thompson, 1990; Tanksley and McCouch, 1997). Transgenic technologies involve the introduction of a new gene, using recombinant DNA technologies, and include now familiar examples such as cotton and maize Bt, genetically engineered for insect resistance (Shelton et al., 2002); incorporation of herbicide tolerance genes (Nair et al., 2002); and transgenic rice with genes for vitamin A production (Ye et al., 2000).

This flourish of new technologies is cloaked in a rapidly expanding lexicon of esoteric jargon. Some of the more relevant terminology is explained within an agricultural context in the Appendix.

3. Relevance of biotechnology to African agriculture

Whilst the Green Revolution provided substantial gains for many people in Asia (Douthwaite and Ortiz, 2001), much of sub-Saharan Africa shows no such yield increases. Almost all of the increase in production can be attributed to increased acreage and reduced fallows. With a growing malnourished population, widespread poverty and major health issues, all agricultural practices that sustainably increase yield, improve health and nutrition, or help to alleviate poverty need to be considered. In an agricultural environment characterized by minimal mechanization, limited irrigation and low use of inputs such as fertilizers and pesticides, biotechnology could play a significant role (Wambugu, 1999; Miflin, 2000; Khush, 2001). In particular, genetic engineering could be used to target major agricultural problems affecting African staple crops. In addition, biotechnology innovation offers new opportunities to explore avenues of progress in areas of major concern, such as health, through the development of edible vaccines to protect against HIV, malaria, pneumonia and many gastrointestinal infections.

Uptake of biotechnology depends on many local economic, political and scientific factors. Some of the determinants are:

- *Increased research capacity*. For example, southern Africa already has advanced biotechnology research capacity and has approved transgenic crops for commercial release, but in western and central Africa there exists only fragmentary agricultural biotechnology capacity related to diagnostics and tissue culture, while there is virtually no ability for gene cloning and transgenesis.
- *Appropriate agricultural priorities*. Genetic engineering could be used to target major agricultural problems affecting African staple crops, such as: insect pests of cowpea; nematode infestations of yam and plantain; viral diseases in cassava; parasitic plants invading a variety of crops; drought susceptibility in cowpea; cyanide production in cassava; or poor nutritional properties of yam and cassava.
- *Participation of local farmers*. Some farming groups in sub-Saharan Africa have adapted to greater technological change. Thus, for instance, many cotton growers or rice farmers now use irrigation. These farmers may be predisposed to more rapid incorporation of new biotechnology products.
- *Existing crop knowledge*. Some crops such as maize and soybean have been subjected to a number of transgenic modifications and could be more rapidly introduced than crops such as yam, on which almost no work has been done using genetic engineering.

3.1. Equity and the right to participate

Concerns have been raised in Europe that Africa may become the dumping ground for unproven biotechnology products produced in the North. Nevertheless, the choice of whether to exploit specific technologies and products is the prerogative of national governments. This will require expertise in the specific agricultural needs of each country, as well as familiarity with its cultural, economic and political constraints.

Choosing the most appropriate tools for sustainable agriculture in sub-Saharan Africa requires partnerships between all stakeholders: the government, farmers, researchers, industry, consumers and the public. It also requires technology and tools that are equitable and within the reach and understanding of all stakeholders. The ability to critically question, adapt, implement and improve the new biotechnology tools made available can only come from involvement (Herrera-Estrella, 1999; Wambugu, 1999); with greater knowledge, expertise and capability comes the opportunity to create greater benefits. However, much of sub-Saharan Africa suffers from poor infrastructure and meagre resources, both human and financial. There is still much need for international assistance and collaboration to increase participation.

3.2. Addressing African concerns and needs

In contrast to the GMO controversy that rages in Europe over issues such as usurping God's role, labeing and uncertain environmental risks, African concerns over the use of biotechnology run far wider and deeper. While ethical, environmental and health safety issues are of global interest with regard to genetically modified organisms (GMOs), in much of the world, biotechnology advances are principally driven by the prospect of improving the financial bottom line of farmers. However, in Africa, molecular biotechnology could address much more significant concerns such as food security, poverty, malnutrition and disease. African concerns relating to biotechnology include:

- a pressing need for gains in agricultural productivity to achieve food security and alleviate poverty;
- a need for new paradigms and approaches to tackle chronic malnutrition and poor health;
- the need to conserve African biodiversity and mitigate environmental degradation;
- the lack of enacted biosafety regulations throughout much of sub-Saharan Africa and the danger of possible exploitation with inappropriate or unproven products;
- the global technology divide, which restricts sub-Saharan African access to the latest biotechnology information, tools and products;
- prejudiced and selective information on both sides of the debate, spread by vociferous NGO's and profit-driven multinationals; and
- an imbalance in negotiating power, resulting from lack of control and ownership of biotechnology tools and products, and of financial resources for legal and economic access.

Most of these concerns are related to deprivation of access to the technology, rather than negative side-effects from its deployment. In part, this reflects the far greater potential that biotechnology holds for developing countries, where health and nutritional needs are far more pressing (Wambugu, 1999).

3.3. Incorporating African crops and farming practices

Africa is the centre of diversity for several crops such as sorghum, millet, white yam, cowpea and African rice, which, together with cassava, maize and plantain form the essential components of most African diets. Except for maize, these crops have been the subject of little research and are likely to receive scant biotechnology interest outside of the region. In contrast, the genomes of thale cress (*Arabidopsis thaliana*) and Asian rice (*Oryza sativa*) are available for all to read. These two species serve as windows to an understanding of all flowering plants at the molecular level. Indeed, there is an ambitious plan to decipher the function of every *Arabidopsis* gene (about 25,000) by 2010 (Chory et al., 2000). In the drive for greater productivity, certain crops also receive close examination. One indicator of the relative level of molecular understanding can be gleaned from the number of nucleotide sequences deposited in rapidly growing databanks (Table 1). As with most other matters, those crops most vital to the agricultural industries of the developed world attract the most attention, including maize, soybean, rice, barley, wheat, tomato and potato. Two of these crops, rice and maize, are also important staples in the developing world. However most crops that constitute the essential core of most African diets, as mentioned above, barely register in the global molecular stakes. Disappointingly, they are subjected to no greater inspection than minor crops such as carrots or parsley, and less than pea, alfalfa or onion. Even petunias and goldfish are better represented than most African staples. Indeed, our pet rabbit commands greater molecular scrutiny than all the African crop staples combined. Cash crops show a similar pattern. For example cotton, important in the USA, has more than 12,000 sequence entries, whereas oil palm, cacao and coconut, with production restricted to the developing world, are represented by less than 300 entries combined. The foreseeable future is unlikely to herald any significant shift in global focus. Therefore, crops important to Africa need Africa-driven initiatives to attract the molecular spotlight.

Table 1. Number of nucleotide sequences of selected organisms deposited in the GenBank database as of April 2002

Organism	Number of sequences
Flowering plants (all species)	2,306,855
Arabidopsis thaliana	311,271
Soybean	252,326
Maize	247,747
Asian rice (*Oryza sativa*)	211,010
Tomato	162,023
Barley	157,560
Wheat	75,481
Potato	69,580
Cotton	12,113
Pea	1,378
Alfalfa	1,123
Onion	1,115
Cassava	946
Sweet potato	473
Petunia	404
Carrot	340
Musa sp. (all species of banana and plantain)	241
Cowpea	203
Yam (all species of *Dioscorea*)	191
Parsley	171
Cacao	150
Oil palm	83
Groundnut	82
African rice (*Oryza glaberrima*)	39
Coconut	13
Dioscorea rotundata (African white yam)	3
Human	5,658,006
Domestic rabbit	5,690
Goldfish	503

Another factor is that farming practices in sub-Saharan Africa differ substantially from the highly mechanized, high-input systems that operate in the developed world. African farms are generally much smaller and more heterogenous in function and design. Consequently, biotechnology in Africa needs to incorporate a wider range of solutions, sensitive to diverse needs, and involving and empowering local communities (Douthwaite and Ortiz, 2001), as well as developing indigenous expertise to facilitate local adoption.

3.4. Illusory savings from imported products and technologies

Biotechnology is an expensive enterprise with a significant time lag between research in the laboratory and impact in the marketplace. As an alternative to developing transgenic products within sub-Saharan Africa, it may seem more judicious to import products that have already passed rigorous testing, such as transgenic maize resistant to corn borer. However, this restricts products to crops and agricultural needs primarily addressing the developed world, and would ignore many of Africa's major crops or preferred varieties. In addition, such products may not target the greatest needs or have optimal efficacy under African environmental conditions and agricultural practices.

Another more creative approach could be to contract out the development of transgenic African crops to multinational corporations with traits desired by African farmers, such as cowpea resistant to pod borer. This course of action has several drawbacks, however:

- it entrenches economic subservience;
- it ignores the fact that the greatest costs are on the development side of R&D;
- it suppresses the establishment of capacity to monitor, modify and adapt products to African needs; and
- it is an *ad hoc* solution that inhibits the long-term development of indigenous biotechnology expertise for local identification, assessment and production in the future.

A more promising solution would be to develop partnerships with international centres that have an on-going commitment to the agricultural needs of the developing world, such as the Consultative Group on International Agricultural Research (CGIAR), a grouping of 16 international agricultural research institutes or facilities, such as the International Laboratory of Tropical Agricultural Biotechnology that specializes in long-term research on cassava. The Strategic Alliance for Biotechnology Research in African Development (SABRAD) also links African research and higher education institutions with other CGIAR centres, such as CIMMYT and IITA, and with the US Department of Agriculture (USDA) and US universities.

3.5. Ensuring relevant best practice applications

Molecular biology has now entered the realm of 'big' science with multi-billion dollar, high profile projects, such as sequencing the human genome. In terms of cost-benefit ratios, such projects would seem to hold little value for most of Africa. Large data gathering exercises usually require even greater investment in analysis and further experimental enquiries to convert such data into useful information. As stated above, most of Africa's major crops hold little molecular interest for the developed world. Complete sequencing and gene function analysis of crops such as cassava, yams or cowpea will elude scrutiny for many years. Instead, these crops need to be approached with techniques that are sequence independent and more pioneering such as developed by Jaccoud et al. (2001), in which genomic variation can be rapidly assessed without any prior sequence data. In addition, the use of gene transactivators randomly inserted into the genome can allow broad testing of gene function and large-scale screening for novel, agriculturally useful traits without specific characterization of the genes involved (Moore et al., 1998; Rorth et al., 1998; Weigel et al., 2000). These techniques require little local infrastructure capability and can be readily applied to many crops and agriculturally desirable traits.

4. Challenges to the implementation of biotechnology

Agriculture in sub-Saharan Africa is constrained by several circumstances: productivity levels well below global averages; unstable governments; inadequate transport infrastructure; and a fragmented, internationally uncompetitive, agricultural business sector. As molecular biotechnology is an expensive, highly specialized technology, it may not appear to be the most appropriate solution to African agricultural needs. Furthermore, other challenges potentially hamper the development and implementation of this technology.

4.1. Lack of infrastructure

Molecular biotechnology has come to dominate agricultural research in the North, yet it barely exists in Africa. Why? The lack of infrastructure may seem to be the most obvious answer. With the exception of South Africa, sub-Saharan Africa is bereft of reliable electricity and clean water, let alone high technology facilities. However, the apparently obvious answer is probably wrong. Many of the great discoveries in molecular biology, such as DNA replication, gene regulation, DNA cloning, agrobacterium based plant transformation and even polymerase chain reaction (PCR) itself, occurred in the 1980s before the era of whole-genome sequencing, DNA robotics, PCR machines, micro-arrays and tailor-made commercially available kits. The desire to acquire tomorrow's equipment to perform yesterday's methodologies entrenches the dependence on knowledge and resources from the developed world. Instead, the ability to craft biotechnology tools relevant in an African agricultural setting will initially require inventive use of locally available resources. Some examples might include developing cassava or yam starch as an alternative gel matrix for DNA separations, or producing locally made enzymes, computer programmes or equipment such as a series of water baths as an alternative PCR machine.

4.2. Biosafety

No human endeavour is entirely free of risk, but prudence demands that we carefully consider possible safety issues, particularly in the case of GMOs whose genetic novelties persist into future generations. The main biosafety issues relevant to the exploitation of transgenic technology are those of environmental impact and human health (Kuiper et al., 2001).

Incorporating novel insect resistance genes into a crop may confer an ecological advantage to the transgenic plant over wild relatives or non-transgenic plants that are more susceptible to insect damage. This could increase the potential of transgenic individuals to spread and become weeds. Alternatively, the transgenes may transfer to wild relatives by pollen spread and confer a selective advantage on the offspring. In addition, concerns have been raised about the effect of transgenes on non-target organisms. For example, transgenic maize with the Bt gene that provides resistance to the European corn borer was reported to have a deleterious effect on the monarch butterfly. This impact resulted from the larvae feeding on milkweed covered with pollen from nearby transgenic crops (Losey et al., 1999). This report was used as a rallying call for protesters to publicize the possible risks associated with GMOs. However, more detailed studies by Sears and others (2001) found that the effect under field conditions was negligible, as the levels of Bt in pollen was low and there was little coincidence between the time of pollen shedding and peak larval activity. This latter result highlights the need for and value of well designed, rigorous risk assessment research. Therefore, provision should be made for appropriate assessments of African crops that may benefit from biotechnology applications.

Similarly, the introduction of new genes may have adverse effects on human health due to unforseen toxic effects or by inducing allergic reactions. However, those risks need to be balanced against standards in common usage. For example, we already tolerate the consumption of foods highly detrimental to the health of many individuals, such as peanuts, shellfish, cow's milk, gluten-containing products, strawberries or Chinese gooseberries. Therefore, we should be guided by the principle that any transgenic crop should not have a greater negative effect than the nearest equivalent non-transgenic form. It is also pertinent, then, to judge the negative effect of not releasing a transgenic product in cases where there are clear health or nutritional benefits.

Other areas of concern of particular relevance to sub-Saharan Africa are the slow implementation of biosafety regulations by national governments and the lack of human and financial resources for risk assessment and management of transgenic foods released into the environment. Resources are woefully insufficient in Africa to adequately assess the food safety of transgenic products, to detect the presence of particular transgenes and to monitor their spread, and to investigate the environmental impact of transgenes in crops important to Africa. While such data do exist for some important crops, such as maize, others including cassava, plantain, yam and cowpea have not been investigated in depth. In addition, risk management practices appropriate to the highly mechanized and controlled agricultural practices in the developed world may not be appropriate in the African context. For example, current refuge strategies may need to be adjusted for the effective long-term deployment of *Bt* insect resistant cotton and maize. Currently, some fraction of these need to be planted with non-transgenic plants to diminish the competitive advantage of rare resistant insect forms (Pittendrigh et al., 2000).

4.3. Biodiversity

The introduction of new cultivars with clear agronomic advantages over traditional lines can lead to not only widespread adoption, but also replacement, which in turn may cause loss of biodiversity. This can lead to loss of many potentially valuable genes. Transformation is often restricted to one or a few cultivars and may subsequently be crossed into an elite line. If successful, this technology may inadvertently encourage narrowing of the genetic base. However, many traditional agricultural practices have also led to reduced crop biodiversity. For example, in Africa the success of cassava and yam (both African and Asian species) have lead to reduced plantings of several native root and tuber crops.

Nevertheless, widespread use of biotechnology tools may help to reverse the trend (Karp et al., 1997). With the advent of new molecular technologies, it has become much quicker and cheaper to screen the plant genetic resource seedbanks and to promote use of a broader genetic base (Tanksley and McCouch, 1997).

4.4. Control and ownership

Development of a viable agricultural industry is dependent on access to the new technology. However, as the developed world prospers from greater agricultural biotechnology interest and competition, additional barriers are presented to sub-Saharan Africa in the form of control and ownership of the technology. Principally, this occurs in the form of intellectual property rights (IPRs) and has ramifications across all interest groups, be they government, research or commercial. At the national level, many countries in Africa are signatories to the Trade-Related Intellectual Property Rights (TRIPs) Agreement (General Agreement on Tariffs and Trade, 1994). This agreement binds nations to accept fairly stringent IPRs. It also adds the extra administrative burden and costs to establish and implement the agreement. Most companies and universities primarily invoke IPRs in the form of patent protection, which grants monopoly rights for 20 years to inventors. All other parties are excluded from using a patented process or product unless under license. This protection has the potential to inhibit many African countries from developing biotechnology ventures that are initially based on copying IP protected technologies.

5. Opportunities provided by the new biotechnology tools

Molecular biotechnology is still in its formative years. While exciting new technologies, emerging from many laboratories, have yet to reach the market place, even more remarkable ideas currently await testing. And yet, even with work already published, biotechnology offers many promising avenues for crop improvement.

5.1. Augmentation of traditional breeding

Breeding involves screening large numbers of different lines, selecting those individuals with agriculturally important traits, quantifying the responsible genes and incorporating those genes into elite breeding material through several generations of crossing and back crossing to elite lines. DNA technology can assist in the selection process by improved pedigree analysis or gene mining for improved genetic variants; and also in tagging desirable genes in a crossing programme through marker assisted breeding (Lande and Thompson, 1990).

Within CGIAR centers, such as the International Institute of Tropical Agriculture, or in nationally run seed banks within each country there are large germplasm collections that maintain many thousands of valuable wild and domesticated crop varieties. By quantifying the degree of DNA variation it is possible to develop highly valuable pedigrees that decipher the true genetic relationships. This allows the elimination of duplicate copies and the establishment of a core collection of distant cousins that can serve as a representative sample of the entire genetic diversity present within a species. For example, IITA maintains a collection of more than 16,000 cowpea accessions than can be tested for desirable agricultural traits such as drought tolerance or resistance to the parasitic weed, *Striga*. However, screening 16,000 lines is costly and time consuming. Evaluation with new DNA-based technologies can greatly assist the screening process (Karp et al., 1997). By establishing a core collection of a few hundred lines of the most genetically disparate groups, screening and selection can become far more cost effective. When useful candidate lines are identified, the pedigree analysis can be used to report on closely related lines that are likely to also carry the same useful gene but may have improved characteristics.

Through use of the latest DNA microarray technology, the entire genome can be represented as tens of thousands of specific DNA fragments spotted onto a surface just a few square centimetres or in a single drop of liquid. With highly sensitive and specific probes, several hundreds or even many millions of DNA base pairs of genetic material can be interrogated for the presence of a single DNA variant (Jaccoud et al., 2001).

5.2. Advances in crop productivity

Food security in sub-Saharan Africa still presents a major challenge. Agricultural biotechnology can increase productivity by raising yield, either directly through increased photosynthetic efficiency, or by redirecting photosynthate into preferred structures such as seed or tubers. Alternatively, yield increases can be achieved by minimizing losses to pest and disease. For example, plants can be strengthened with genes resistant to insects, nematodes, fungus, parasitic weeds, bacteria or virus. Indirect benefits may also accrue: an aphid resistance gene not only reduces the aphid load but also lowers the opportunities for the spread of aphid-borne viral diseases. Furthermore, reduction of insect damage results in fewer sites becoming available for secondary infections by fungi or bacteria. Similarly, transformation with stress tolerance genes can alleviate losses due to abiotic factors such as drought, high salt or aluminium toxicity. Transgenic technology can also help to reduce the costs of farm inputs such as pesticides and fertilizers, while the use of herbicide tolerant genes can lower labour costs associated with weeding. Increased productivity, by even a few dollars per hectare, will have a far greater relative impact in sub-Saharan Africa, where poverty is still persistent, compared to the developed world.

5.3. Improved health and nutrition

Biotechnology advances can be found that tackle areas not solely related to improving crop productivity, but also address the broader issues of health and nutritional needs. Some recent examples that have emerged include biofortification of crops with improved micronutrient levels, such as ‘golden’ rice, transformed with vitamin A biosynthetic genes (Ye et al., 2000), rice enhanced with the iron avid gene, ferritin (Goto et al., 1999), and improved protein quality enrichment of maize that attracted the 2000 World Food Prize. Although the final outcome of ‘golden’ rice to avert blindness in children may prove to be less golden than the initial promise, the feasibility of the technology suggests that significant gains are possible but will require greater collaboration with plant physiologists, agronomists and nutritionists.

In addition to applying similar types of genes to crops of interest in Africa, other opportunities of particular value in tropical Africa, where medical services are severely limited, are attracting greater interest. Biotechnology offers possibilities to produce acyanogenic cassava, improved starch properties in yam, or biopharmaceuticals, including edible vaccines. In particular, vaccines produced in transgenic plants

(Walmsley and Arntzen, 2000) have shown considerable promise in animal experimental systems. Transgenic potatoes expressing a vaccine to hepatitis B have proven effective in providing immunization when fed to mice (Kong et al., 2001). Alternatively, malaria vaccine expressed in milk from transgenic mice effectively immunized Aotus monkeys against a lethal challenge of the parasite (Stowers et al., 2002).

Transgenic crops with insect or pathogen resistance genes can also have a significant indirect benefit on health by reducing the need for potentially dangerous chemical sprays. For example, to control insect pests of cowpea, farmers in West Africa are using highly toxic insecticides intended for cotton. Cotton, which is often grown in cowpea regions, attracts high levels of insecticide use, due to its significant pest problems and high value as a cash crop. In contrast, there are few approved insecticides effective for cowpea, and those that exist are often difficult for farmers to obtain. This leads to the common use on cowpeas of pesticides that are not approved for human consumption, yet remain undetected in the marketplace. The use of transgenic cowpea (and cotton) with insect resistance genes could significantly mitigate this health risk.

Biotechnology could also yield significant gains in relation to the health and nutritional needs of livestock. Transgenic approaches to fodder crops, such as cowpea, could address factors such as reducing ammonia production that gives rise to bloat in ruminants, decreasing plant lignin content to improve digestibility, better balanced protein composition to counter amino acid deficiencies, and vaccine production. Vaccines against trypanosomes, transmitted by blood sucking tsetse flies, could open up vast tracts of currently unsuitable grazing lands to livestock.

5.4. Precision engineering

The first generation of transgenic crops are based on just a few genes, such as insect and herbicide resistance genes, randomly inserted into the genome. These genes are coupled with simple, non-specific control elements. New advances in molecular biology allow far greater specificity and control of transgene expression including the insertion of genes into the chloroplast (Daniell et al., 2002). The chloroplast houses its own genome that carries genes primarily involved in photosynthesis. It is passed to the offspring through the female egg cell. Chloroplast DNA is not present in pollen. This means that any foreign gene inserted into the chloroplast genome will not be able to pass to neighbouring crops or wild relatives through pollen transfer. In addition, if genes such as the insecticidal Bt genes are involved, then the potentially deleterious effects on non-target pollen feeders, such as the larvae of the monarch butterfly as reported, can be avoided.

Other technologies allow the following possibilities: precise site-specific gene insertion and modification (Rice et al., 2001); deletion of unwanted antibiotic and herbicide resistance genes used in the selection of transformed cells (Zuo et al., 2001); and/or tissue-specific gene expression through transactivation gene technology (Moore et al., 1998; Weigel et al., 2000).

5.5. Horizon technologies

Newer technologies under development offer even greater possibilities for improving agriculture in Africa. Some examples include diversity generation using novel mutagenesis techniques, apomixis, gene silencing (Baulcombe, 1999) and homologous recombination (Putcha, 2002).

One method to provide additional material for breeding programmes is through inducing mutations with carcinogens or through high-energy radiation. However, the mutations generally destroy gene activity, and thus are nearly always deleterious. In contrast, alternative technologies can provide positive approaches that give rise to a gain of function mutation (Rorth et al., 1998). More than half of all genes expressed in plants or animals are involved in regulation, that is, determining when, where and to what level other genes are expressed. From work by Doebley and colleagues (1997), the difference between the erect unicomb form of maize and the highly branched nature of teosinte (*Zea mays mexicana*), a grassy relative, is determined by a mere two-fold change in expression level of a single regulatory gene. Indeed, it is expected that plants as different as banana, rice, cassava and cowpea have an almost identical set of genes, but most of the diversity is held captive by changes adjacent to the gene that regulate the amount, conditions and locations of cells in which the gene is turned on. For example, all maize plants carry a gene that confers resistance to a major insect pest: the stem borer. However, only in one Argentine cultivar is this gene expressed in the stem, allowing effective control of the insect pest. In other cultivars the gene is turned on in the roots which is not the preferred ecological niche of the stem borer. By using technology borrowed from fundamental studies of the fruit fly, *Drosophila* (Rorth et al., 1998), it is possible to change the expression of the insect resistance gene to the stem in other maize cultivars. This exciting approach to large-scale diversity generation could help to unlock the evolutionary potential held within any one plant to produce a far greater range of different forms than is available within the germplasm collections.

Apomixis is clonal reproduction through seed, in which all offspring are genetically identical to the mother plant. Apomixis is widespread amongst flowering plants, including blackberry and dandelions, but is rare amongst agriculturally important crops. Unravelling the genetic control of apomixis would open up many new breeding strategies of crucial importance to Africa (Moffat, 2001). For example, the genetically heterogeneous offspring of hybrid maize, if apomictic, would be able to breed true without reduction in yield gains achieved through hybrid vigour. This would allow farmers to retain seed for the next crop rather than purchasing hybrid seed each season from the seed companies. Even more significant is the application of apomixis to vegetatively propagated crops, such as cassava, yam and sweet potato. These crops are not maintained through true seed due to the highly heterogeneous nature of any progeny. Apomixis would permit rapid production of large numbers of genetically uniform seed that are easy to transport and lack much of the pathogen load abundant in vegetative propagules, such as cassava stem cuttings or yam and sweet potato tubers.

6. Seeds of promise: developing a sustainable agricultural industry

How do we create *de novo* an autonomous biotechnology community that is relevant, enduring and effective when faced with no funds, decaying infrastructure and an impoverished research base?

6.1. Access to biotechnology knowledge, products and techniques and use of indigenous knowledge

One critical constraint to the effective exploitation of biotechnology is access to information. With well-resourced libraries, students and researchers in the industrialized world are awash with information about biotechnology. Completion of the human genome sequence was announced to a fanfare of publicity and the journals *Nature* and *Science* widely promoted ‘free’ access to many excellent articles unravelling the genome’s mysteries. However, although freely available, access is far from free for many people living in sub-Saharan Africa. Faced with severely limited computer capacity, prohibitive subscription fees and a paucity of skilled teachers to lay transparent the insights from daily discoveries in molecular biology — access remains a mirage. Nevertheless, the Internet remains the most promising provider of up-to-date information. With modest donor support for building computer capacity and the goodwill of publishers, online admission to journals, textbooks and patent records could be made cheaply and widely available throughout much of sub-Saharan Africa. Exposure to the latest discoveries would help to inspire students and teachers, rejuvenate the aspirations of researchers, and provide policy-makers with insights into biotechnology issues such as biosafety, intellectual property rights, and economic opportunities. Online information could provide a keystone for stimulating biotechnology innovation in Africa (Keese, 2001).

On the other hand, greater use should also be made of indigenous knowledge, either through farmers, opinion leaders or communities. In the highly heterogeneous agricultural environment of sub-Saharan Africa, it is necessary to embrace the viewpoints, constraints and opportunities of those people who hold the most intimate knowledge of the land and farming practices, so that the most appropriate advances will be designed and implemented. Indigenous knowledge can also be important in the areas of neglected crops or plants with medicinal properties.

6.2 Education, research and training

Education and research are central components of a local, sustained involvement in biotechnology. Education, particularly at the post-graduate level, provides fertile ground for much of the cutting-edge research on which biotechnology is built. However, many African PhD graduates in molecular biology have received their training in advanced laboratories in Europe or North America. Those graduates who do return face disillusionment and frustration from inadequate equipment and funding.

Greater emphasis is required to provide high quality education locally as this is likely to identify the most talented students, retain a higher proportion of graduates more attuned to local agricultural priorities and facilities, provide a larger pool of suitably trained technicians and researchers for national agricultural research institutes, and to influence general attitudes to be globally competitive.

One mechanism to boost the research and training capacity of the human resource base is the widespread establishment of centres of excellence, competitively selected and accredited according to standards that operate in Europe or North America. Funding of these centres could be coupled with fellowship schemes to fund teams of the brightest post-graduate students. These teams should encompass a broad range of disciplines to foster synergistic effects. For example, the inclusion of engineering students could lead to an in-house capability for construction of essential equipment; computing students to the creation of novel bioinformatic programmes; or economic students to the assessment of the implementation and impact of proposed products. Other strategies to boost the effectiveness of these centres include short-term training fellowships in advanced laboratories, mentoring of students via email, and incorporation of distance-learning packages.

Agricultural biotechnology is likely to impact upon the lives of all Africans. Awareness programmes that involve and engage the support of the local communities should be initiated to promulgate the underlying concepts of biotechnology, including the possible benefits to farmers and consumers, and to address crucial issues such as biosafety, bioethics, food safety and risk management. In the rurally dominated, heterogeneous landscape of sub-Saharan Africa, it is important that these programmes include hands-on educational units that can travel to any community, no matter how remote.

6.3. Networks and strategic alliances

Biotechnology garners many consortia with diverse interests, including university-industry partnerships to enhance research efforts, and various NGOs and lobby groups to promote and provoke public interest. Through the spread of the Internet, email and video conferencing offers great opportunities for Africa to link common interest groups, both nationally and internationally. Given the small, highly fragmented and dispersed agricultural biotechnology research community in Africa, networking is particularly important (Machuka, 2001). It is one means of developing the 'critical mass' research base required for the efficient exploitation of the new technologies by integrating overlapping interests through shared resources and information. One of the most promising networks is SABRAD (http://caens.tusk.edu/sabrad/) which links African groups with international collaborators. Similarly, networks such as the African Biotechnology Stakeholders Forum, have proved effective in raising awareness and understanding of agricultural biotechnology in the general community, particularly in East Africa. This locally developed initiative serves as a valuable model for adoption in other parts of Africa.

At present, the gap in biotechnology between the developed world and sub-Saharan Africa has become a chasm. To effectively bridge the agricultural needs of sub-Saharan Africa with the biotechnology expertise in the developed world requires strong alliances at all levels. These partnerships should involve governments, universities, agricultural research institutes and multinational business groups. In some cases, international centres such as IITA and CGIAR, play a vital brokering role to transfer the latest research advances to regional institutes, ensuring that technologies are relevant and adapted to the needs of African agriculture. In this regard, the internationally competitive biotechnology capacity available in South Africa could serve as an important model and be used to forge a wider range of partnerships. On-going support by government donor agencies will also continue to play a vital role in strengthening those linkages and promoting the development of biotechnology products that reach the marketplace.

6.4. Legal, economic and social policy frameworks

To establish and sustain a viable agricultural industry in sub-Saharan Africa requires strong commitment from national governments in both financial and policy areas. Associated with this commitment is the need for greater regional co-operation, not only in research, but also policy coordination. For example, harmonizing biosafety legislation would be of great significance. Under present farming practices, the introduction and spread of transgenic plants in much of tropical Africa is unlikely to recognize national borders. In addition, there is the opportunity to achieve cost savings through economies of scale, especially when extended to the establishment of joint regulatory bodies.

Government regulations on imports, phytosanitary controls, as well as taxes and permits, can also influence the uptake and dissemination of the technology. However, long-term government financial support of both the public and private sectors is also necessary to promote major improvements in agriculture in Africa. Funding from outside donor agencies could be used as leverage to encourage national government involvement in biotechnology.

6.5. Human resources

The most pressing constraint to establishing a credible agricultural biotechnology industry in sub-Saharan Africa is the need for vastly increased human resources. A recent report by Alhassan (2001) on agricultural biotechnology research capacity in five West African countries reveals that Nigeria, the most populous country in Africa, has less than 70 people with advanced degrees in molecular biology. A similar situation exists throughout West and Central Africa. East Africa has more suitably trained people, but only South Africa possesses internationally competitive biotechnology research centres. Similarly, educational institutions throughout much of sub-Saharan Africa are bereft of suitably skilled teachers to establish adequate biotechnology courses to train and inspire future generations.

The dearth of human capacity in biotechnology also extends to support services, such as computing programmers, engineering and electronic specialists, biotechnology-fluent policy-makers, NGOs and entrepreneurs, medical toxicologists and food-safety experts, and bioethicists. To establish such a diverse human resource base that will persist and expand requires on-going commitment from national governments.

6.6. Entrepreneurial spirit

Ultimately, the long-term sustainability and growth of a viable agricultural industry depends upon the involvement and commercial success of the private sector. Initially, this may require partnerships with multinationals, but in many cases it may be government support of local initiatives, including funding business plans for spin-off companies arising from publicly funded research. There is also a need to orient some of the research and development towards outcomes that open new markets or increase trade. For example cassava chips are gaining widespread acceptance as an alternative snack to potato chips; the post-harvest quality of cassava could be improved through research, allowing processors more reliable sourcing of material.

7. Conclusion

Agricultural biotechnology, fuelled by daily research breakthroughs, is likely to radically change the face of agriculture, both in terms of greater efficiency and availability of new types of products to combat disease and malnutrition. Africa stands to capture the greatest gains from agricultural biotechnology. But in a continent wrought from political instability and economic hardship can this new technology be afforded, implemented and sustained? A viable agricultural biotechnology industry needs a solid foundation, which must include committed government support, effective biosafety measures, and a highly educated, entrepreneurial research contingent. Of critical importance is investment in human resources to generate high-impact outcomes from low-cost inputs and meagre infrastructure. This will necessitate greater innovation and vision, not less. Africa came away from the Green Revolution empty-handed; let us strive to ensure that Africans are not denied the fruits of the Biotechnology Revolution.

References

Alhassan, W.S., 2001. The status of agricultural biotechnology in selected West and Central African countries. The International Institute of Tropical Agriculture, Ibadan.

Baulcombe, D.C., 1999. Fast forward genetics based on virus-induced gene silencing. *Current Opinion in Plant Biology*, 2(2): 109–113.

Campbell, K.H., McWhir, J., Ritchie, W.A., Wilmut, I., 1996. Sheep cloned by nuclear transfer from a cultured cell line. *Nature*, 380(6569): 64–66.

Chory, J., Ecker, J.R., Briggs, S., Caboche, M., Coruzzi, G.M., Cook, D., Dangl, J., Grant, S., Guerinot, M.L., Henikoff, S., Martienssen, R., Okada, K., Raikhel, N.V., Somerville, C.R., Weigel, D., 2000. Functional genomics and the virtual plant: A blueprint for understanding how plants are built and how to improve them. *Plant Physiology*, 123(2): 423–426.

Conway, G., Toenniessen, G., 1999. Feeding the world in the twenty-first century. *Nature*, 402(6761 Suppl): C55–58.

Daniell, H., Khan, M.S., Allison, L., 2002. Milestones in chloroplast genetic engineering: an environmentally friendly era in biotechnology. *Trends in Plant Sciences*, 7(2): 84–91.

Doebley, J., Stec, A., Hubbard, L., 1997. The evolution of apical dominance in maize. *Nature,* 386(6624): 485–488.

Douthwaite, B., Ortiz, R., 2001. Technology exchange. *Electronic Journal of Biotechnology*, 4(2) available at: http://ejb.ucv.cl/content/issues/02/index.html

Food and Agricultural Organization (FAO). Biotechnology papers available at http://www.fao.org/biotech/

General Agreement on Tariffs and Trade (GATT), 1994. Agreement on Trade-Related Aspects of Intellectual Property Rights (TRIPs Agreement). Available online at http://www.wto.org/english/tratop_e/trips_e/trips_e.htm

Goto, F., Yoshihara, T., Shigemoto, N., Toki, S., Takaiwa, F., 1999. Iron fortification of rice seed by the soybean ferritin gene. *Nature. Biotechnology*, 17(3): 282–286.

Herrera-Estrella, L., 1999. Transgenic plants for tropical regions: Some considerations about their development and their transfer to the small farmer. *Proceedings of the National Academy of Sciences of the United States of America*, 96(11): 5978–5981.

Jaccoud, D., Peng, K., Feinstein, D., Kilian, A., 2001. Diversity arrays: a solid state technology for sequence information independent genotyping. *Nucleic Acids Research*, 29(4): E25.

Karp, A., Edwards, K., Buford, M., Wosman, B., Morgante, M., Seberg, O., Kremer, A., Boursot, P., Arctander, P., Tautz, D., Hewit, G., 1997. Molecular techniques for biodiversity evaluation: opportunities and challenges. *Nature. Biotechnology*, 15(7k): 625–628.

Keese, P., 2001. Even 'free access' is still beyond the means of most scholars in Africa. *Nature*, 410(6832): 1021.

Khush, G.S., 2001. Green revolution: the way forward. *Nature Reviews Genetics*, 2(10): 815–822.

Kong, Q., Richter, L., Yang, Yu-Fang, Arntzen, C.J., Mason, H.S., Thanavala, Y., 2001. Oral immunization with hepatitis B surface antigen expressed in transgenic plants. *Proceedings of the National Academy of Sciences of the United States of America*, 98(20): 11539–11544.

Kuiper, H.A., Kleter, G.A., Noteborn, H.P., Kok, E.J., 2001. Assessment of the food safety issues related to genetically modified foods. *Plant Journal*, 27(6): 503–528.

Lande, R., Thompson, R., 1990. Efficiency of marker-assisted selection in the improvement of quantitative traits. *Genetics*, 124(3): 743–756.

Losey, J.E., Rayor, L.S., Carter, M.E., 1999. Transgenic pollen harms monarch larvae. *Nature*, 399(6733): 214.

Machuka, J., 2001. Agricultural biotechnology for Africa. African scientists and farmers must feed their own people. *Plant Physiology*, 126(1): 16–19.

Miflin, B.J., 2000. Crop biotechnology. Where now? *Plant Physiology*, 123(1): 17–27.

Moffat, A.S., 2001. Plant biotechnology. For plants, reproduction without sex may be better. *Science*, 294(5551): 2463–2465.

Moore, I., Galweiler, L., Grosskopf, D., Schell, J., Palme, K., 1998. A transcription activation system for regulated gene expression in transgenic plants. *Proceedings of the National Academy of Sciences of the United States of America*, 95(1): 376–381.

Nair, R.S., Fuchs, R.L., Schuette, S.A., 2002. Current methods for assessing safety of genetically modified crops as exemplified by data on Roundup Ready soybeans. *Toxicological Pathology*, 30(1): 117–125.

Nuffield Council on Bioethics, 1999. Report: Genetically modified crops: the ethical and social issues. http://www.nuffieldbioethics.org/publications/pp_0000000009.asp

Pittendrigh, B.R., Gaffney, P., Murdock, L.L., 2000. Deterministic modeling of negative cross-resistance strategies for use in transgenic host-plant resistance. *Journal of Theoretical Biology*, 204(1): 135–150.

Putcha, H., 2002. Gene replacement by homologous recombination in plants. *Plant Molecular Biology*, 48(1–2): 173–182.

Rice, M.C., Czymmek, K., Kmiec, E.B., 2001. The potential of nucleic acid repair in functional genomics. *Nature. Biotechnology,* 19(4): 321–326.

Rorth, P., et al., 1998. Systematic gain-of-function genetics in Drosophila. *Development*, 125(6): 1049–1057.

Sears, M.K., et al., 2001. Impact of Bt corn pollen on monarch butterfly populations: a risk assessment. *Proceedings of the National Academy of Sciences of the United States of America*, 98(21): 11937–11942.

Shelton, A.M., Zhao, J.Z., Roush, R.T., 2002. Economic, ecological, food safety, and social consequences of the deployment of bt transgenic plants. *Annual Review of Entomology*, 47: 845–881.

Stowers, A.W., Chen, L.H. , Zhang, Y.L., Kennedy, M.C., Zou, L.L., Lambert, L., Rice,T.J., Kaslow, D.C. , Saul, A., Long, C.A. , Meade, H., Miller, L.H., 2002. A recombinant vaccine expressed in the milk of transgenic mice protects Aotus monkeys from a lethal challenge with *Plasmodium falciparum*. *Proceedings of the National Academy of Sciences of the United States of America*, 99(1): 339–344.

Tanksley, S.D., McCouch, S.R., 1997. Seed banks and molecular maps: unlocking genetic potential from the wild. *Science*, 277(5239): 1063–1066.

Walmsley, A.M., Arntzen, C.J., 2000. Plants for delivery of edible vaccines. *Current Opinion in Biotechnology*, 11(2): 126–129.

Wambugu, F., 1999. Why Africa needs agricultural biotech. *Nature,* 400(6739): 15–16.

Weigel, D., Hoon Ahn, J., Blázquez, M., Borevitz, J.O., Christensen, S.K., Fankhauser, C., Ferráandiz, C., Kardailsky, I., Malancharuvil, E.J., Neff, M.M., Nguyen, J.T., Sato, S., Wang, Z-Y., Xia, Y., Dixon, R.A., Harrison, M.J., Lamb, C.J., Yanofsky, M.F. and Chory, J. 2000, Activation tagging in *Arabidopsis. Plant Physiology,* 122(4): 1003–1013.

Ye, X., Salim, Al-Babili, Kloti, A., Zhang, J., Lucca, P., Beyer, P., Potrykus, I., 2000. Engineering the Provitamin A (-Carotene) Biosynthetic Pathway into (Carotenoid-Free) Rice Endosperm. *Science,* 287(5451): 303–305.

Zuo, J., Niu, Q.W., Moller, S.G., Chua, N.H., 2001. Chemical-regulated, site-specific DNA excision in transgenic plants. *Nature. Biotechnology,* 19(2): 157–161.

Appendix

Biotechnology: The use of biological processes or organisms for generating products of benefit to humankind. Biotechnology covers the use of techniques for the improvement of agriculturally important plants, animals and micro-organisms, including the production of pharmaceuticals, industrial chemicals, vaccines or monoclonal antibodies. Traditional biotechnology approaches include long practised techniques such as herbal remedies, cheese making and brewing. In contrast, much of our current advances rest upon manipulations of DNA. This includes the controversial area of genetically modified organisms, the principal focus of this article, as well as non-transgenic techniques such as marker-assisted breeding, wide crosses between different plant species and cloning whereby the genetic constitution remains unaltered, such as the cloning of the sheep Dolly (Campbell et al., 1996).

Marker-assisted selection: Identification and use of DNA markers closely linked to one or more genes of agricultural interest to increase the speed and efficiency of selection during the breeding process.

GMO (genetically modified organism): An organism whose genetic constitution has been altered by the introduction, change or elimination of specific DNA sequences or genes through the application of recombinant DNA technology. As defined here, GMOs do not include organisms arising from random mutations induced by chemicals or radiation, artificially induced wide crosses between different species, or animal cloning.

Recombinant DNA technology: A set of techniques that enable one to manipulate DNA, including identifying genes, cloning genes, examining the function of cloned genes, and producing large quantities of a gene product.

Cloning: 1) The process of cell division to give rise to a population of genetically identical cells that may develop into a whole organism, for example, in 1997, Ian Wilmut and colleagues cloned the sheep Dolly from an udder skin cell; 2) Gene cloning whereby a DNA sequence is incorporated into a self-replicating DNA molecule to give rise to multiple copies of that sequence. This is often an intermediary step in producing a GMO.

Transgenic: An organism (most commonly a plant or animal) in which a foreign gene (a transgene) has been incorporated into the genome. The term transgene may encompass artificial genes and sequences stably transferred into the genome, as well as genes from other organisms.